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RTNS-II: Experience at 14-MeV Source Strengths Between 1 x 10^{13} and 4 x 10^{13} n/s

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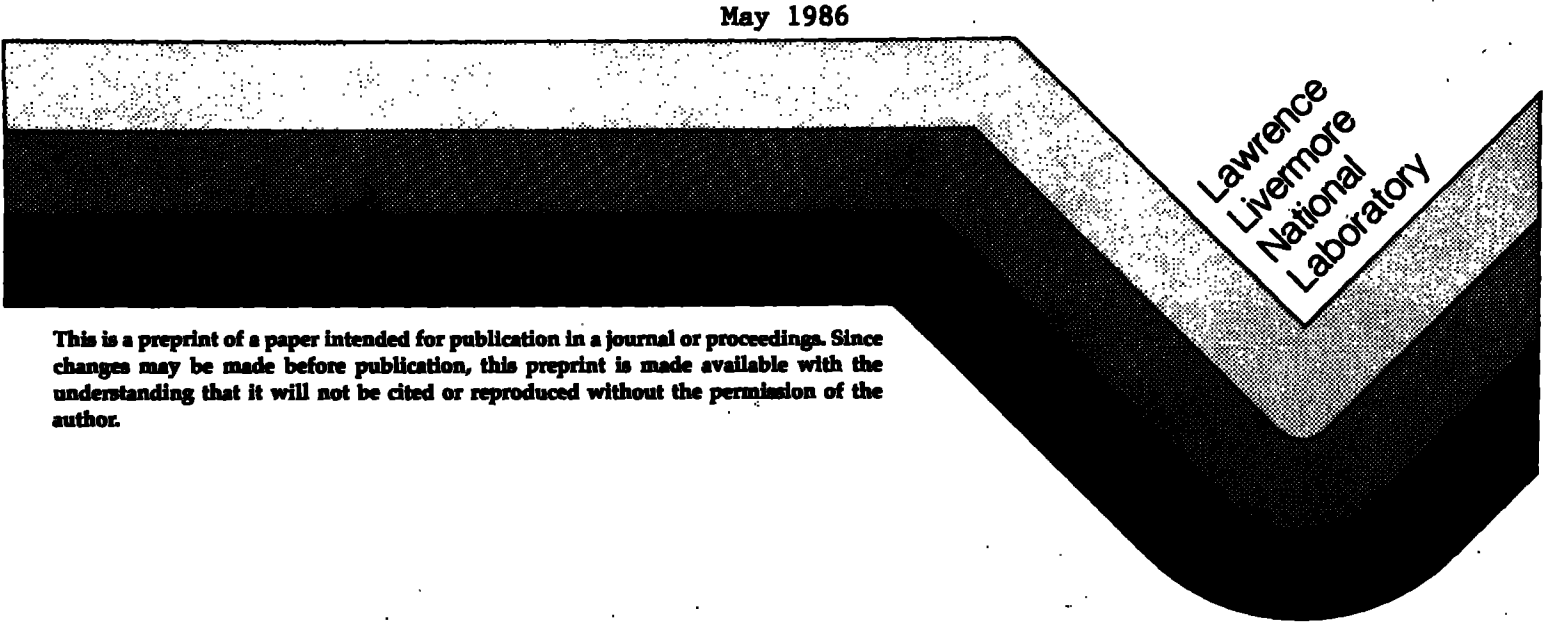

RTNS-II: Experience at 14-MeV Source Strengths Between 1 x 10^{13} and 4 x 10^{13} n/s*

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INTRODUCTION

Ten years have passed since the design of the two RTNS-II (Rotating Target Neutron Source-II) 14-MeV neutron sources. These sources have now operated for a total of almost twelve accelerator years, providing irradiation services for a wide variety of nuclear physics and materials science experiments. With the closure of this irradiation facility scheduled for next year, a review of the successes and failures of its design concepts is particularly appropriate. Originally designed to operate at a peak neutron source strength of 4 x 10^{13} n/cm^{2}s, the sources have basically reached that goal. Essential in design of the sources was not just the production of high fluxes in themselves, but development of a facility that could support complex and changing irradiation experiments. The facility was to operate at high plant factor and at an acceptable cost in both dose delivered to operating staff and releases to the environment. The success of this endeavor is reviewed as well.

The possibilities of higher source strengths are discussed in light of the operating experience to date and of new technologies that may be applied to the problems of high flux generators of this type. Similarly, changes in the ancillary equipment that would provide more efficient or safe operation are also indicated.

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1. Original Design Concepts and Expectations: 1974-78

Fundamental to the design of the RTNS-II sources was the experience with the RTNS-I source. Booth and Barschall[1] were the first to explain that the apparently anomolous target lifetime of up to 100 hours obtained with RTNS-I was a consequence of the use of a monoatomic deuteron beam. This beam produced the maximum useful neutron yield from the solid target without displacement of the tritium contained in the target by accompanying molecular species. As the RTNS-I source utilized an accelerator designed for both pulsed neutronics and intense flux production, this monoatomic beam existed as a result of a somewhat fortuitous design feature; the high-current duoplasmatron ion source in the high voltage head utilized a bending magnet to separate the ion species and provide monoatomic beam to simplify the bunching optics. Development of a clever splash-cooled 15-cm titanium-tritide target rotating at 1100 rpm provided a source strength near 2×10^{12} n/s at D^+ currents of 8 mA.[2] The accelerator was modified to produce D^+ beams up to 20 mA, and the target was enlarged to a diameter of 23 cm. By 1973, peak source strengths of 6×10^{12} n/s were produced routinely, and a variety of fusion-related materials irradiations and cross-section measurements had been performed.

The successful operation and understanding of RTNS-I, coupled with the energy crisis-induced expansion of the fusion programs of the United States, led the Livermore Laboratory to propose construction of a new intense source based upon the principles of RTNS-I. The final proposal, funded for construction in 1976, envisioned two neutron sources. Each source was to be capable of peak strengths of 4×10^{13} n/s with potential to be upgraded to 1×10^{14} n/s. Design concepts for the facility were discussed at some length in 1977;[3] a brief summary is given here. The arrangement of major accelerator and target systems is shown in Fig. 1.

Accelerators

Each accelerator was to produce a beam of 150 mA of D^+ at 400 keV, which was to be transportable to a target room several meters from the high voltage platform and able to be focussed to a spot size of 1 cm in diameter.

Rather than the magnetically coupled 60 Hz power supply of RTNS-I, 1500 Hz solid state voltage multiplier supplies purchased from Emile Haefele et Cie were utilized. Each supply is rated at 300 mA and is upgradable to 500 mA by the addition of a second rectifier string. To provide power in the 10 m^2 high voltage platform, a 75-kVA three-phase isolation transformer is used. Inside the high voltage platform, voltages of 480, 220 and 115 are distributed at single- or three-phase as required by electronics and power supplies. Control of all components in the high voltage terminal is by robust single-channel fiber optic links; readout of terminal parameters is by both a multiplexed fiber optic link and a backup television link also transmitted via fiber optics.

The ion source selected for use is a seven-aperture reflex arc source. The extraction supply installed originally was rated at 25 kV, 0.5A. In operation on a test stand duplicating the 90° double focussing magnet selected for species separation, the source produced currents of up to 100 mA of H^+, suggesting its adequacy for this application. The acceleration tube design is uniform gradient, utilizing five electrodes of 10-cm aperture with an active length of 25 cm. Actively cooled electrodes fabricated of chromium-coated copper with molybdenum inserts shape the accelerating field. The vacuum envelope of the acceleration tube is a 46-cm diameter ceramic vacuum brazed into four sections; O-ring joints join the separate sections. Pumping was originally by directly coupled turbomolecular pumps. A single 2000-l/s pump was installed in the high voltage terminal behind the analysis magnet and two 2000-l/s pumps on a plenum directly following the acceleration tube. The original vacuum system was all stainless steel with O-ring seals near the ion source and metal seals in the section between accelerator and target. Two 1000-l/s turbomolecular pumps removed the gas load at the target.

Currents in the transport section in the ion source terminal are read from both fixed and insertable electrodes, while beam position is determined with a television viewer that observes the recombination light from ionization of residual gas in the beam line. Beam diagnostics in the transport system at ground potential utilize graphite limiting apertures on which power can be read both electrically and calorimetrically, and optical monitors similar to those in the terminal. The beam spot on the rotating target is observed by a

television camera looking down the transport system from behind the bending magnet in the terminal. All elements in the entire accelerator system are shown in Fig. 2.

Target

The tritium containing target layer selected from trials on the RTNS-I machine was chosen for these sources. After evaluating several thicknesses and types of tritium occluders, a nominal thickness of 10 μm of titanium was found to retain tritium for the longest useful lifetime while minimizing tritium inventory. Targets lasted for an average of 100 hours before the yield decayed to half the initial value. After that time, the neutron output of the target decayed more rapidly. Initial yield from a fresh target was 2.5×10^{11} n/mA.

Mechanical design of the target system envisioned operating the target layer within the envelope of the same thermal cycle experienced on RTNS-I, thus achieving the same lifetime. To accomplish this, the target diameter had to be increased to 50 cm, and the speed of rotation increased to 5000 rpm. At this speed, cooling of the target by immersion in a thin film of water was no longer possible because of drag considerations; thus, an internally cooled target was required with rotating fittings for water feed and drain. Target substrates were made by diffusion bonding of two layers of copper alloy, one etched to contain the cooling channels. Initial substrates were 23 cm in diameter. To reach the high rotating speed desired, a differentially pumped bearing was built to support the target. Mechanical loads are carried by a large aperture precision ball bearing assembly, and an air-levitated differentially pumped seal provides vacuum isolation. The bearing assembly is driven by an air turbine. The assembly is mounted on a cart with all utility interfaces running through a single panel to allow for remote changeout. The target cart was also designed to support the irradiation experiment and provide utility services to it as well.

Ancillary Systems

Containment and control of prompt and residual radiation without compromising convenient access to the working points of the sources were important design criteria for this facility. The floor plan of the facility

is shown in Fig. 3. To contain the prompt radiation, walls of the target cells were made 2.5 m thick, yielding an attenuation factor of 10^8. Reinforcing bars in the cell walls were placed no closer to the surface of the concrete that 40 cm to reduce the dose in the target room contributed by activation of the iron. Target rooms are kept at negative pressure during operation, and the exhaust from them passed through particulate filters to minimize the inventory of airborne species and activated dust released up the facility stack. Temperature in the target rooms was stabilized by wholly contained cooling systems in each room.

Controlled access work space for the repair and storage of activated or contaminated irradiation assemblies and target assemblies was built into the facility. Included in this 300 m^2 hot workroom were a hot cell with traditional remote manipulators, a storage vault for temporary storage of used targets, fireproof vaults for longer term storage of new targets, and hoods for maintenance of tritium contaminated equipment. A remote handling system was included to transport target carts between the hot cell and the target rooms.

Protection against tritium released by the targets during operation and reduction of the amount exhausted up the facility stack is provided by online catalytic tritium scrubbers through which the exhaust of all pumps in the facility passes. Tritium content of the air in all accelerator and target rooms, in the maintenance areas, in the enclosures around the scrubbers and in their input and output streams, and in the facility exhaust stack itself, is continuously monitored and recorded. The presence of tritium throughout the facility and in the body tissues of the operating staff is monitored by a combination of swipe tests and urine analyses. Fortunately, the 10 years experience gained with RTNS-I provided useful guidance in establishing protocols for contamination control. All target containers are opened under hoods in case of particulate release, and respirators and gloves are used in all target changing operations. A fundamental goal in establishing rules for all handling of radioactive materials was to keep individual annual dose below 0.5 rem. Except in emergencies, no entry to target pits was to be made for the first 8 hours after extended operation.

2. Operating Experience and Modifications: 1978-1986

The construction phase of the RTNS-II project reached completion in November of 1978.[4] Unfortunately, the Magnetic Fusion Program was able to provide only 60% of the funding estimated necessary to operate the two sources in the 24-hour per day mode for which they were designed. Consequently, only one source was operated for the next 4 years for 16 hours per day. Since the accelerator had been tested successfully by operating one system as a prototype with hydrogen beams during the construction project, the accelerator design staff were reassigned to different Laboratory activities. Operation during the first few years reached source strengths of about 1.5×10^{13} n/s and the first few 50-cm targets were produced. Because of the reduced operating week and low source strength, maintenance could be easily accomplished, and the systems were not stressed to their design levels.

In February 1982, a joint agreement to operate RTNS-II was signed between the Ministry of Science, Education and Culture (Monbusho) of the Government of Japan and the Department of Energy of the United States. For the first time, resources adequate to operate both sources continuously and to push them to higher strengths were available. Since that time, source strengths have reached nearly 4×10^{13} n/s and availabilities of about 85% have been obtained in 24-hour per day operation for 5-day weeks.[5] Initial and current parameters of the sources are given in Table I. The agreement between the US and Japan expires in Feburary 1987. At that time, the facility will be shut down and preserved for possible future use.

Accelerators

In general, the accelerators have operated with excellent reliability and simplicity. The limiting feature has been the atomic species output of the ion source. In early operation, this fraction was as low as 30% of a total extracted current of 150 mA. In 1982, the original 25-kV extraction supplies were replaced by 35-kV supplies of the same 0.5 A rating. This modification, combined with raising the arc power from 2.5 kW to 5 kW has raised the atomic species current available for acceleration to over 150 mA, with target currents of up to 150 mA possible. Successive developments have produced

extraction grid sets that last over 1000 hours and cathode assemblies that run for up to 250 hours before replacement. Atomic fraction still remains below 50%, however, and the terminal pumping system has been upgraded to a total of 4000 l/s capacity.

The acceleration columns have operated without modification or failure except for three occasions: two when insulators shorted on the electron suppression electrode at ground and one when a cooling line in the accelerator terminal failed into the vacuum system. However, the sparking rate of the tubes is very nonlinear with current and voltage. Sustained operation at the design voltage of 375 kV (nominal beam energy of 400 keV) is not possible without excessive sparking. Lowering the column voltage to 330 kV reduces the sparking rate to 4-5 per hour at currents near 135 mA, and produces little penalty in neutron output. The cause of the sparking is throught to be x-ray induced charging of the smooth inner surfaces of the insulators. A new tube of identical electrostatic geometry, but with thicker electrodes and ceramics with convoluted inner surfaces has been built. This tube will be installed and tested if the operating schedule allows. Sections of the two tube types are shown in Fig. 4.

Operation of all high voltage systems and power supplies has been excellent. Only nominal maintenance has been necessary for components in the high voltage terminals. Less transient induced damage has been observed than expected, a tribute to the excellent power distribution and grounding protocols in the design. The main high voltage supplies have required occasional replacement of diode sections, and each isolation transformer was opened shortly after initial operation to correct grounding errors on the secondary leads. Use of highly derated equipment has yielded excellent reliability.

Transmission through the acceleration tube and the transport system to the target is virtually 100%. However, the occasional thermal loading of elements during tuning caused welds to fail in the original hard-sealed stainless steel beamline. Gradually, most of the stainless steel transport system has been replaced by water cooled copper components with elastomer seals. The two 1000-l/s pumps at the target were replaced by two 2000-l/s pumps to improve operating vacuum there. Static pressure throughout the

system is in the low 10^{-7} Torr range. Operating pressures are typically 10^{-4} Torr near the ion source, 10^{-6} Torr in the transport region and 10^{-5} Torr at the target. All of the original Sargeant-Welch turbo pumps have been replaced by Balzers pumps.

No satisfactory visual diagnostic has been developed for tuning the beam spot on the rotating target. The light produced by the beam on the target varies with target and gas pressure, and has never been successfully correlated with the fluence measured by radiographic means. A combination of sputtering and radiation damage rapidly darken the window through which this light is observed. Similarly, there is no real time flux diagnostic; fluence is still measured for each irradiation by foil activation. The geometry of the target assembly and the irradiation packages precludes use of the sort of neutron imaging systems that might otherwise be thought useful.

Target

Original operation was with 23-cm targets whose substrates were fabricated at LLNL and then shipped to Oak Ridge National Laboratory for titanium deposition and tritium loading. At currents in the 40-70 mA range, these targets did indeed have useful lifetimes of 100-150 hours; however, considerable variation in target quality (as evidenced by failure early in operation) and in lifetime was observed. In parallel with the operation on 23-cm targets, the production sequence for 50-cm targets was developed. Approximately one hundred 23-cm targets were used before operation with them was discontinued.

Difficulties in control of the diffusion bonding, hydrostatic deformation and pressure testing processes involved in production of the target substrates led to unacceptable losses in the process. The diffusion bonding technique was abandoned and replaced with an electrodeposition process. Target substrates are now made by depositing a thin copper layer over etched cooling channels that are filled with conductive wax. The wax is subsequently melted and blown out. High success rates are obtained now, and the resulting target has slightly better thermal properties as the electrodeposited copper has higher conductivity than the alloy previously used. Partly because of the variation observed with the ORNL loaded targets and partly to establish total

control of the thermal cycles to which the targets were subjected in all preparation steps, we decided to perform the tritium loading operations for the 50-cm targets at LLNL. A dedicated loading system was built in the LLNL Tritium Facility for this mission.

Routine operation with 50-cm targets began in 1982. To date, a total of 75 of these targets have been produced. Average initial yield of a new target is 2.1×10^{11} n/s-mA; average total yield before replacement is 1.1×10^{19} neutrons. In this period of operation, two targets have failed mechanically while in operation by collapsing under atmospheric pressure and loading caused by rotation. These failures are thought to have resulted from radial expansion of the target rim. The design of the target system relies on radial stiffening by a graphite composite hoop into which the target is installed. Elastic deflection of the target shell under vacuum loading brings the target rim into contact with the stiffening hoop. An undersized target may deflect too far before contacting the stiffener, then buckle under the additional loads imposed by rotation. More careful control of target dimensions has prevented a reoccurrence of this failure. In both incidents, the rotating bearing suffered major damage, but there was no violent disassembly of the target system.

Ancillary Systems

Performance of the various supporting systems has ranged from vital and excellent to irrelevant and virtually useless. The tritium scrubbers have functioned with very little maintenance, removing tritium from the exhaust of the vacuum systems at factors approaching 10^6:1. After several years of operation, it became evident that the annual release of 20-80 curies resulted from roughing out operations during which the scrubbers are bypassed. Installation of a large volume tank in the roughing system allows these surges of gas to be buffered from the scrubbers. The stored gas is then slowly processed by the scrubbers. Release of tritium from the facility is expected to be less than 10 curies per year with this modification.

Because of the complexity of the experiments fielded (typically multi-week irradiations under high vacuum and at carefully controlled temperatures ranging from 20° K to 720° K), the original concept of

withdrawing the target assembly and experiment for weekly target changes has never been used. The weekly cooldown period over each weekend has allowed access to the target rooms on Monday mornings for both target changes and repair or adjustment of experiments. Neither the remote handling equipment nor the hot cell have ever been used as originally intended.

Radiological Experience

Dose levels to operating staff remained below the 0.5 rem annual target during the first few years of operation of the facility with the average annual dose to workers actually handling maintenance operations being typically 100-150 mrem. The contribution to total dose from tritium retained in the body tissues was 10% of the total dose. No neutron dose has ever been recorded for any staff member.

After switching to 50-cm targets and beginning 24-hour operation of both sources, the average annual dose climbed to 250 mrem. Three or four individual doses in the 500 mrem to 1.25 rem range were recorded in the years 1983 and 1984. This increase in dose resulted from higher residual activities caused by higher source strengths, extra maintenance operations in debugging larger target assemblies, and the more delicate operations and longer times required to change the larger targets. More stringent control of personnel entry to the activated areas, increased hardware reliability, more carefully defined target replacement procedures and rotation of staff have reduced the annual doses to their previous levels.

In this period, both the long lifetime activation and tritium contamination levels in the target cells increased. More elaborate entry and exit and protective clothing requirements were instituted to prevent the spread of contamination. However, in the summer of 1984 a major spread of tritiated particulates (perhaps 100 microcuries total inventory) was detected throughout the facility. A shutdown of several weeks was required to clean the facility before operation could be resumed. The origin of the particulates (determined to be from a target) and the exact mechanism of spread of them throughout the facility remains uncertain. What was clear was that the daily sequence of swipe testing had failed to detect the contamination because of the exceedingly low exchange of tritium from the

particulates to the scintillation solution used in the swipe testing. The particles represented little biological hazard because of this low exchange rate and because they were not of the size to be retained in the lungs. Procedures were modified to require careful and slow scanning of personnel and equipment with thin window x-ray detectors before leaving contaminated areas. Full body suits, gloves, boots and face shields are now used in target areas. Flow paths of people and components through the facility were modified to provide more limited pathways for particulate spread and a convenient station for monitoring for contamination. Since that time, no further spread of contamination has occurred.

3. Future Possibilities

Discussions of improvements or upgrades of the technology of this particular source technology are somewhat colored by the scheduled termination of operations at RTNS-II. This closure will leave RTNS-I at Livermore, Oktavian at Osaka and FNS at Jaeri, all operating in the 4 x 10^{12} n/s range as the strongest 14-MeV sources available until Oktavian-II becomes operational. Nevertheless, as there are no plans for the construction of more intense neutron sources in this energy range for any applications in the near future, it is perhaps useful to document the ideas relevant to the further development of this approach.

Accelerators

Design of the RTNS-II sources anticipated the possibility of an upgrade to 1 x 10^{14} n/s in the power supplies and shielding of the accelerator systems. By adding another rectifier stack to the high voltage supply, it is possible to raise the current rating of the supplies to 500 mA at 400 kV. Similarly, a second isolation transformer can be added to the high voltage platform to increase the power available at 400 kV to 150 kVA, adequate for any likely ion source. Utilization of this capability requires an ion source producing 0.5 A of atomic deuterium without excessive molecular components. At present, developments in the use of large RF ion sources suggest that this step may be possible. Sandia Albuquerque is currently debugging a 50 A RF

source built by TRW Corporation for thermal testing of tokamak limiter materials. Initial short pulse operation of the source is encouraging.[6] LLNL has discussed with TRW the purchase of a version of this source rated at 2 A of D^+. Sufficient power exists in the high voltage terminal to operate the source. The new acceleration tube would probably accelerate at least 0.5 A of current; above that level the redesign of the electrostatic optics might be required. The main attractions of the RF source are high atomic fraction and absence of cathode structures. Recent experiments with RF sources having ceramic arc chambers and external antennas offer the hope that erosion of antenna insulators may be avoided as a limiting problem.

The balance of the present accelerator system is adequate for operation at higher currents unless a newer ion source generates a significantly greater gas load. It would be difficult to increase the delivered pumping speed on the accelerator without major and unwieldy rebuilds of the vacuum system. The optical components of the transport system presently operate at fields indicating complete space charge neutralization of the ion beam; no serious problems are expected at currents a factor of ten higher. Total costs of the changes necessary to try to produce 10^{14} n/s are under \$750K. The reconfiguration of an accelerator to produce 1.5 A of D^+ at 400 keV for a 4×10^{14} n/s source is estimated to cost \$5-6M. All projected costs assume continued operation of at least one source.

Target

Construction of a target able to operate at higher powers with an acceptable lifetime is the major uncertainty in the extension of this technique to higher source strengths. A major study[7] of such an extension has been performed by David Tuckerman of LLNL. His modeling of the present target suggests that improvements in the aspect ratio of the cooling channels, thinning the layer between water and target layer, doubling the target speed and diameter, and using microfabrication techniques to encapsulate the tritium-bearing material in refractory layers and place a palladium drain layer in the target would produce a target able to operate at the 750 KW/cm^2 necessary for a 4×10^{14} n/s source. The development and fabrication costs for this target system are estimated to be \$4.5M.

Ancillary Systems

Most outstanding of the problems for a source operating at higher source strengths will be the need for fully automated exchange of targets. At present, we are operating near the limit of the duty factor-dose tradeoff. If complicated experiments are to be exchanged and positioned remotely, the cost of the utility support and remote handling systems will easily exceed the cost of the source itself. The point may rapidly be approaching where it will be more cost effective to relocate the source than the experiment because the former has a lower activation level and can be more easily serviced. The failure of the conventional hot cell to be useful for maintenance operations at the present source strengths suggest that ample storage space, spares and a clever glove box system would meet these needs in a more cost effective and realistic manner. Costs of facility improvements adequate for operation at 4×10^{14} n/s are estimated at $5M.

Summary

The RTNS-II Facility has met the technical and program goals set out at the time of its proposal in 1974. The solid target neutron generator technology still has reserve for further development. An investment of $15M could provide yet another factor of ten enhancement in source strength. As RTNS-II provides both irradiation data and valuable operating experience with high duty factor tritium contaminated systems, a further investment in this technology seems appropriate if the fusion budget enters another period of growth.

Acknowledgements

The operation and improvement of RTNS-II has been made possible only through the efforts of a dedicated group of scientists, engineers and technicians over a long period. Clint Logan, Dale Heikkinen, Bruce Schumacher, Dexter Massolletti and George Harter are particularly appreciated for their contributions to the success of RTNS-II in general and to this review in particular. The author looks forward to working with them on future projects with great pleasure.

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Table I

Initial and Present Characteristics of RTNS-II Neutron Sources

	Initial	Present
Total energy of beam	360 keV	365 keV
Ion source extraction voltage	25 kV	35 kV
Ion source arc current	40 A	50 A
Maximum beam current	45 mA	150 mA
Maximum neutron production	10^{13} n/s	3.5×10^{13} n/s
Target substrate size	23 cm	50 cm
Target tritium content	4.4×10^{7} MBq	1.8×10^{8} MBq

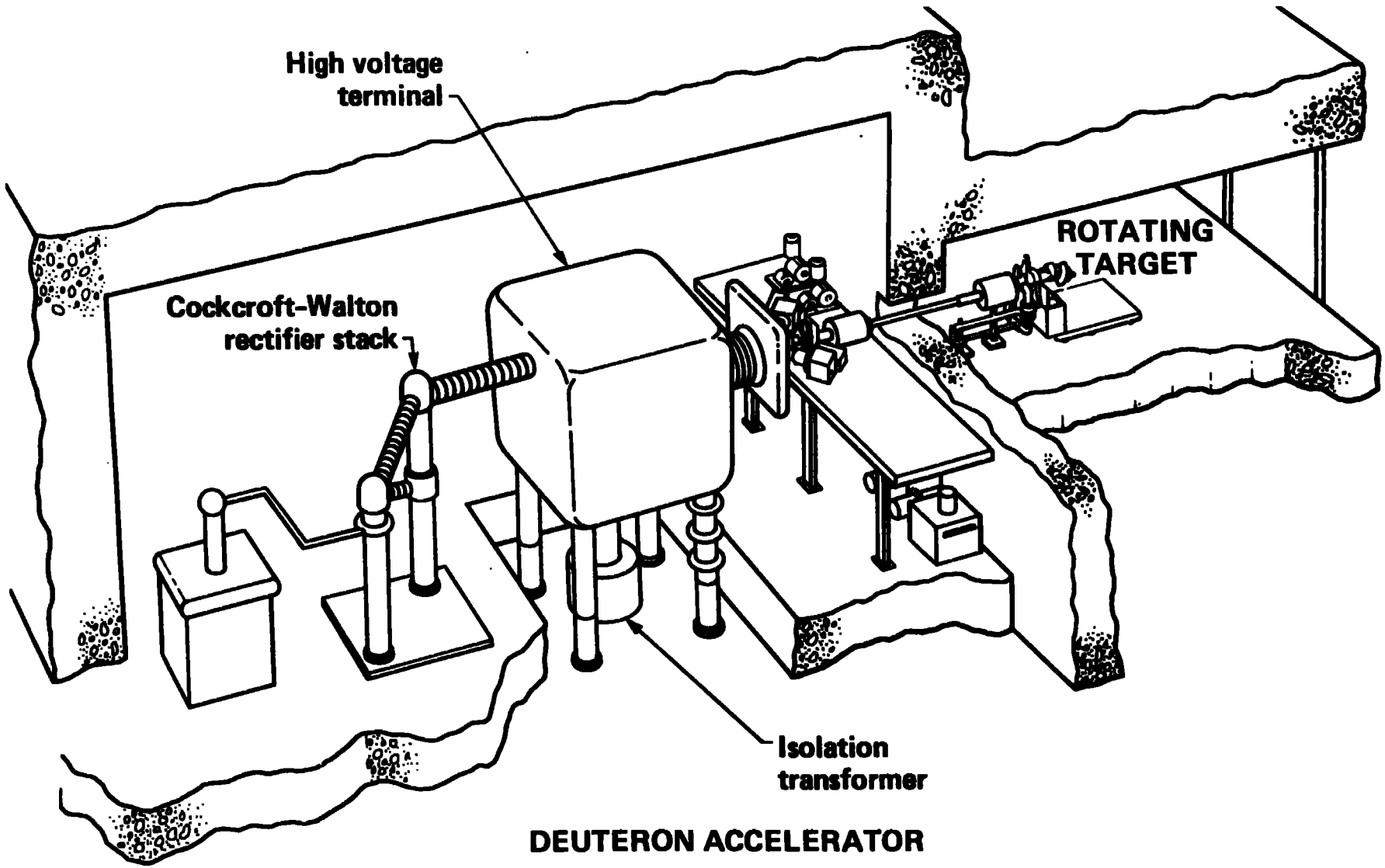
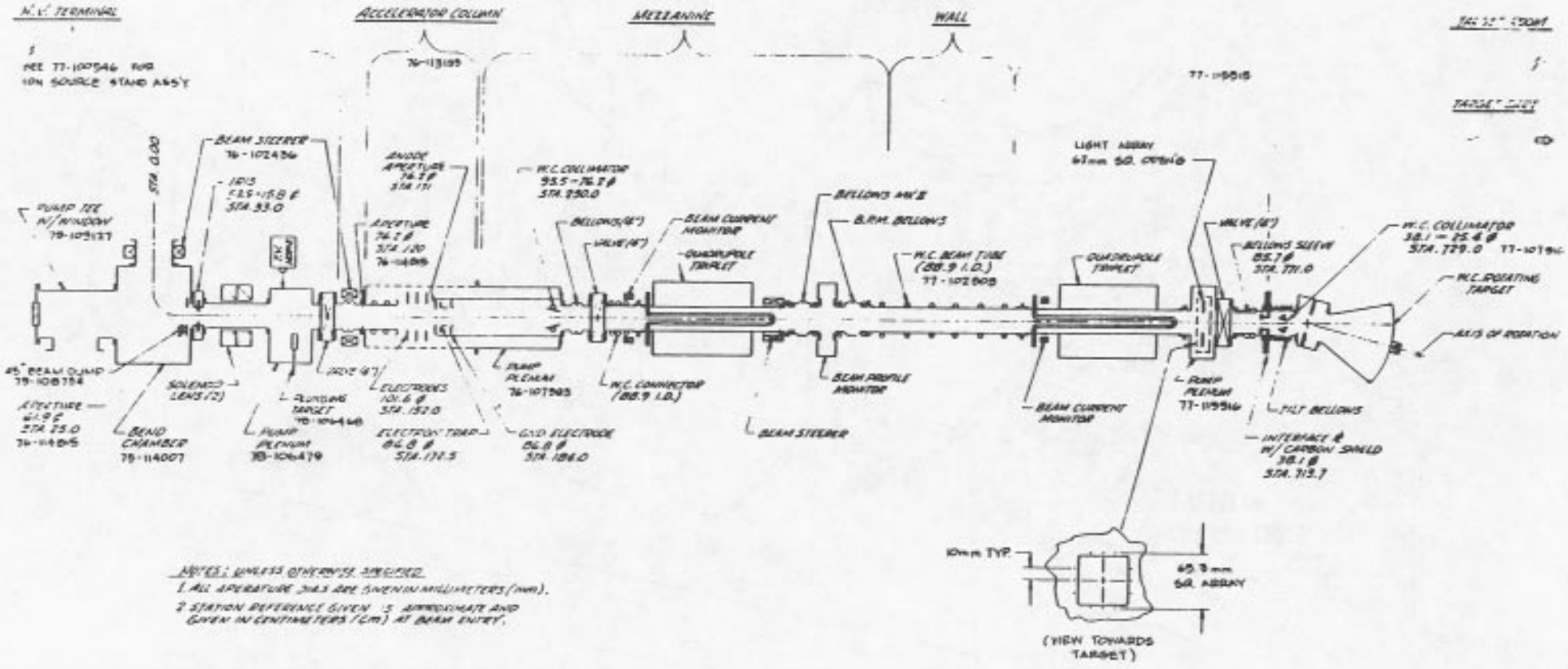


Figure 1

RTNS-II Neutron Source Schematic



NOTES: UNLESS OTHERWISE SPECIFIED
1. ALL APERATURE DIAS ARE GIVEN IN MILLIMETERS (mm).
2. STATION REFERENCE GIVEN IS APPROXIMATE AND GIVEN IN CENTIMETERS (cm) AT BEAM ENTRY.

Figure 2

Beam Transport System

RTNS - II FACILITY - BLDG. 292

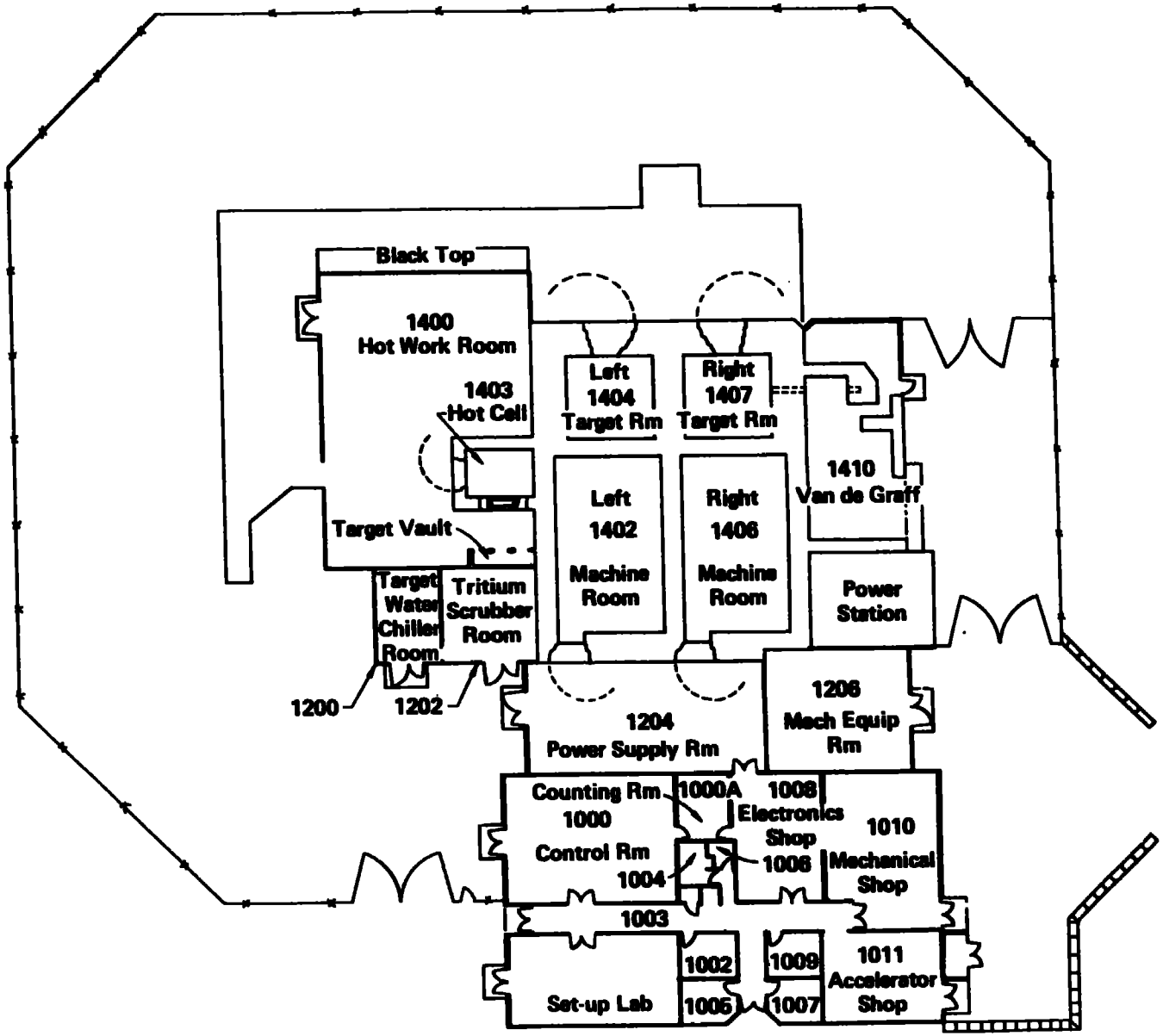
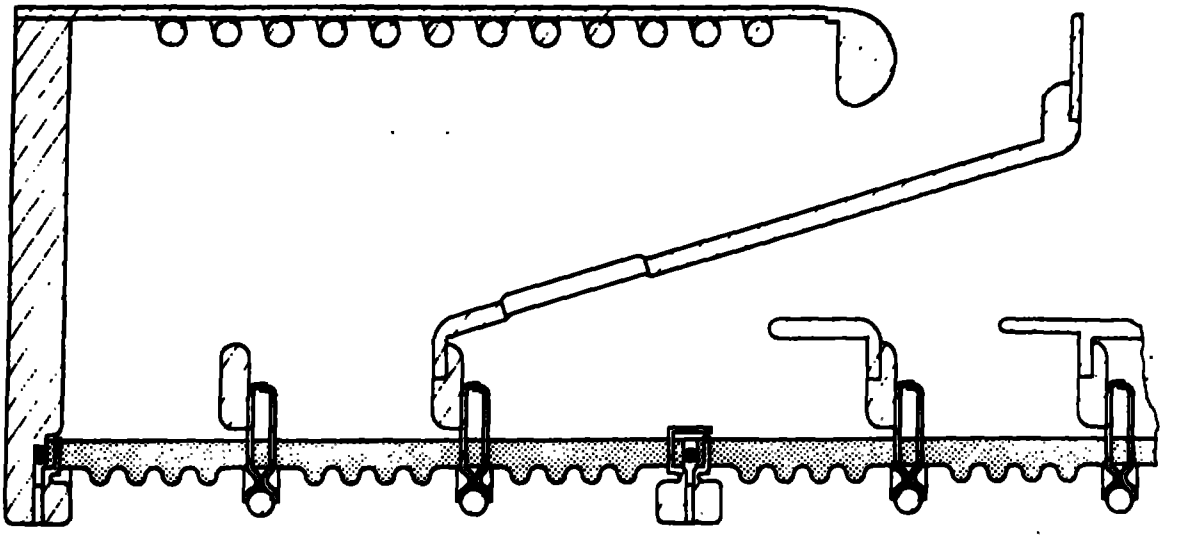


Figure 3

RTNS-II Facility - Bldg. 292

(a)



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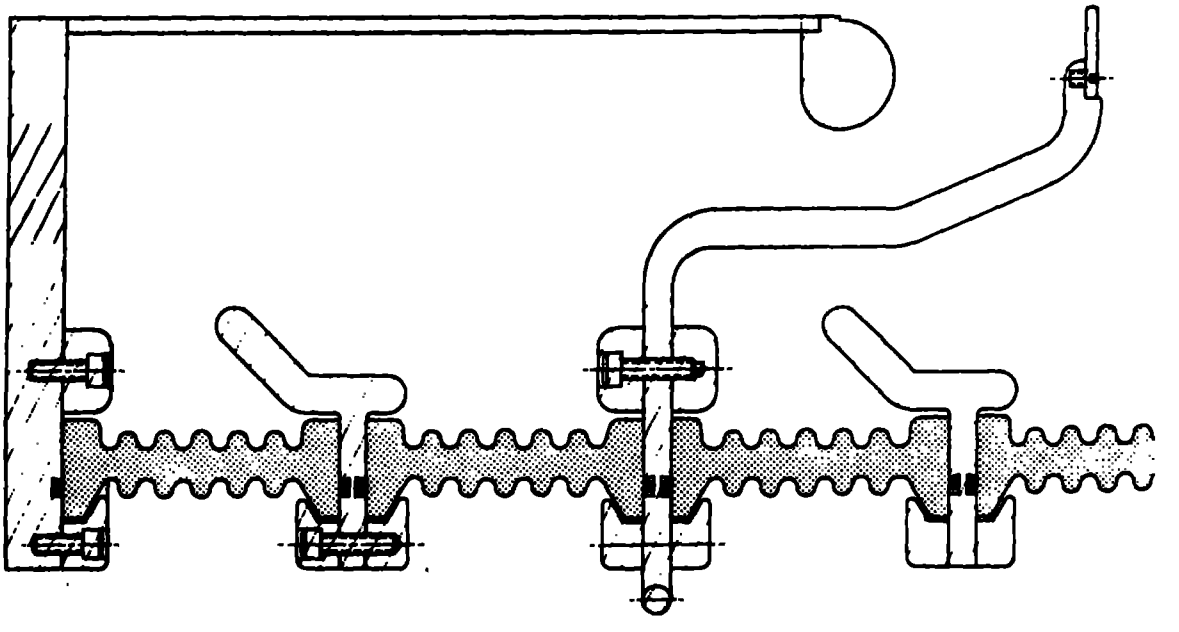

Figure 4
Old and New Acceleration Tube Details

Microstructure details of new targets

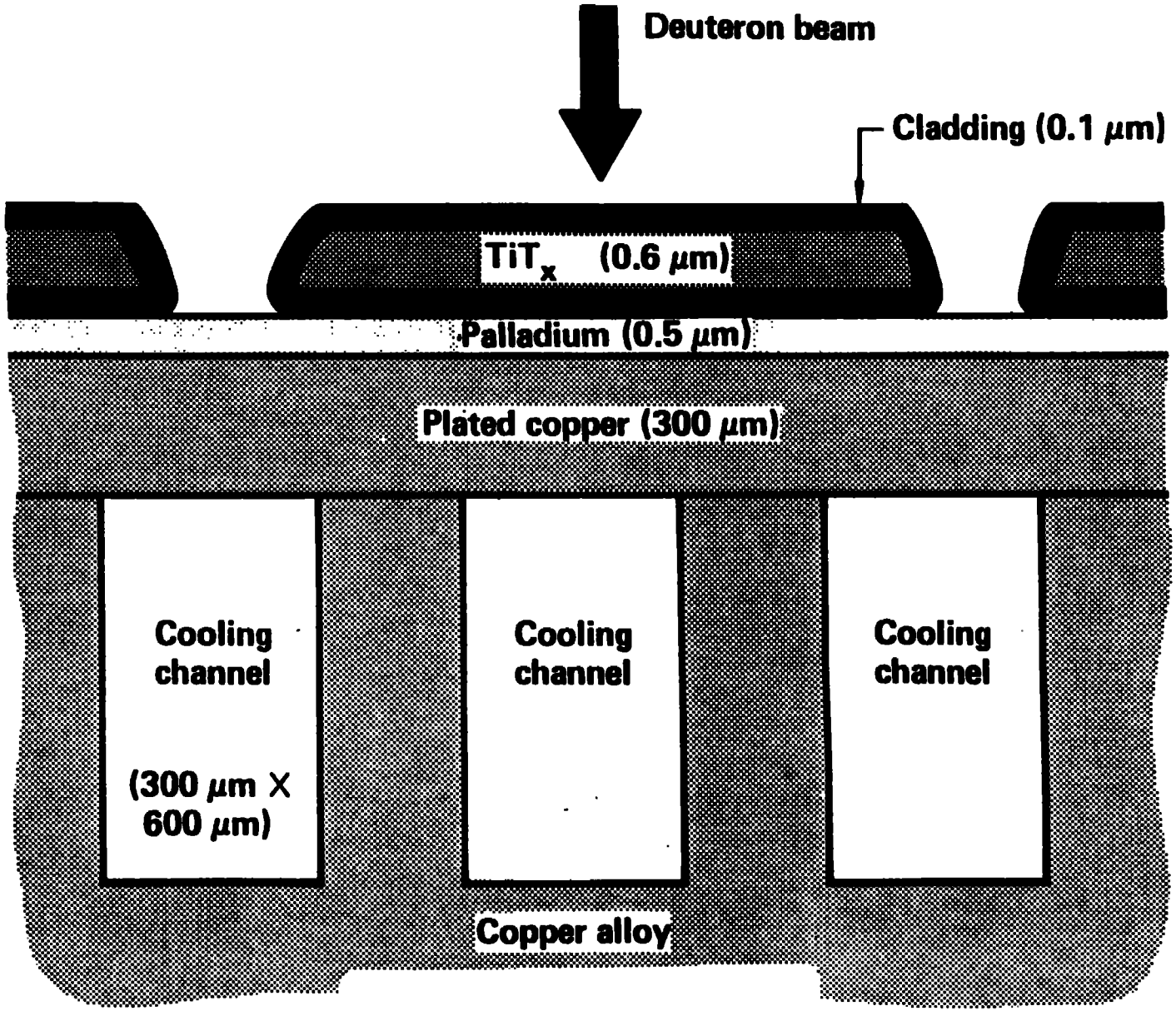

Figure 5

Schematic of Layered Target